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Investigation on the tribological characteristics of lubricated Al_2O_3-TiC surface

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Abstract

Lapping process is one of the most important processes in modern hard disk drive manufacturing. Using lubricant in the lapping process does not only reduce the friction but also transfers heat and captures debris away from the surface contacts. The effects of tribological parameters on the lubricant characteristics and friction regime were investigated, using tribometer. The tribological behaviors of the lubricated alumine-titanium carbide (AlTiC) surface with different types of lubricants were also investigated. The coefficient of friction values of stainless steel ball sliding on the lubricated surface exhibited much lower than dry surface. The variation of normal force and sliding speed did not affect lubricant regime on dry surface. For the lubricated AlTiC surface with both ethylene glycol-based and oil-based lubricants, the friction regime changed as a function of both normal force and sliding speed. Scanning electron microscopy confirmed deeper and wider wear tracks on dry lubricant than those with lubricants.

1. Introduction

Magnetic hard disk drive (HDD) is still another important component in computer for data storage by writing and reading magnetic bits of the binary information on the magnetic solid disk. Generally, a HDD consists of media platter, actuator arm, motor, control circuits, and the read-write head. The data read-write head, so called "slider" is a small part moving above the media platter and transform platter's magnetic field into electrical current (data reading) or transform electrical current into magnetic field (data writing) during data access operation. The structure of slider consists of multi-layers of thin film materials, which is well-designed and grown on alumina-titanium carbide (Al_2O_3-TiC) substrate, known for industry as: "AlTiC" substrate. This AlTiC substrate is a two-phase composite material consisting of approximately 70 wt% alumina (Al_2O_3) and 30 wt% titanium carbide (TiC). It is a hot isostatically pressed (HIP), high density ceramic material [1]. These multi-layers were deposited on the AlTiC substrate and form unique tunneling magnetoresitive (TMR) structure to sense and create the magnetic signal during read/write data on the disk. As the slider flies over the media disk during the operation, the gap between them is extremely small, just only 7-9 nanometers, in order to receive and transfer magnetic signal. The specific design etched pattern: air bearing surface (ABS) on the AlTiC surface underneath the slider helps to provide the pressure contribution to keep constant space between slider above disk during HDD operation [1-3].

During HDD slider fabrication process, the defect-free, ultra-smooth surface is the first priority requirement, in order to achieve the higher recording densities and small flying height. Therefore, surface finishing quality of the slider is an important key to ensure the optimum performance of HDD. The slider lapping process is the most crucial step in fabrication process to achieve that ultra smooth surface on the AlTiC substrate after cut from the wafer [2,3]. Lapping process is a process in which two surfaces (slider and lapping plate) are rubbed together in order to remove material to a designed thickness and smoothen the surface roughness [1-3]. There are many factors in the slider lapping process, such as normal load force, lapping speed, size of diamond lapping particles and the properties

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of lubricants, to be considered and optimized. At the lapping contact between moving surfaces, friction force is generated and the material removal mechanism starts. Employing lubricant in lapping process is not only reducing the unnecessary friction force but can also help to transfer heat and debris away. This prevents the surface defect formation, such as smear to occur. Moreover, some additives in lubricants can also provide a protection against material corrosion [4,5]. For tribology points of view, AlTiC shows regions of high and low friction, which coincides with the alumina phase for the high friction region and the TiC phase for the low friction region [1]. Generally, wear of this material is a complex function and depends on contact geometry, surface roughness, micro-structure, grain sizes, fracture toughness, speed, load, temperature, duration, environment and lubrication [6].

In this work, we studied the tribological characteristics and lubrication behaviors on the AlTiC surface, using the ball-on-disk tribometer under the lubricated condition. The effects of different types of base lubricant, applied normal force and surface sliding speed were investigated, as relationships to the fundamental tribological parameters such as coefficient of friction (COF) and the friction regimes in the process. This can provide an optimized guidance for the lubricant design.

2. Experimental

The 3-inche diameter double-side polished AlTiC substrates were obtained from KYOCERA Asia Pacific Pte Ltd. These AlTiC substrates have surface hardness about 2000 HV and the surface roughness about 10 nm. The tribological measurement was done by using the Bruker CETR-UMT-2 microtribometer with a ball-on-disk configuration. There are 2D-force sensors that are used to measure the sliding friction force between the upper and lower specimens and controlling the loaded force, as shown in Figure 1 [7]. This microtribometer was equipped with SUS304 stainless steel ball as a probe. The load force on the AlTiC surface was varied from 0.1-0.5 N and the rotational speed was set between 300-3600 mm·min^{-1}, to match the actual fabrication condition. The tribological measurements were performed on the lubricated AlTiC surfaces, in comparison with the dry AlTiC surface (without lubricant). Two types of electronic-grade lubricant were used to lubricate the surface of AlTiC substrate: ethylene glycol (EG)-based lubricant and oil-based lubricant. All lubricants were obtained from Western Digital Corporation. During the measurement, the surface friction force was recorded and the COF was calculated as a function of both applied normal force and surface sliding speed. After that, the friction regime for each measured condition was determined, according to the power law relationship between the frictional force exerted on the surfaces and the physical properties of material, plane and lubricant in the context of ice friction. In theory, this frictional force is viewed as heat generated per unit displacement [8,9]. The surface morphology of the tested AlTiC substrates were inpected with JEOL JSM-6400 scanning electron microscope (SEM) for the wear track analysis.

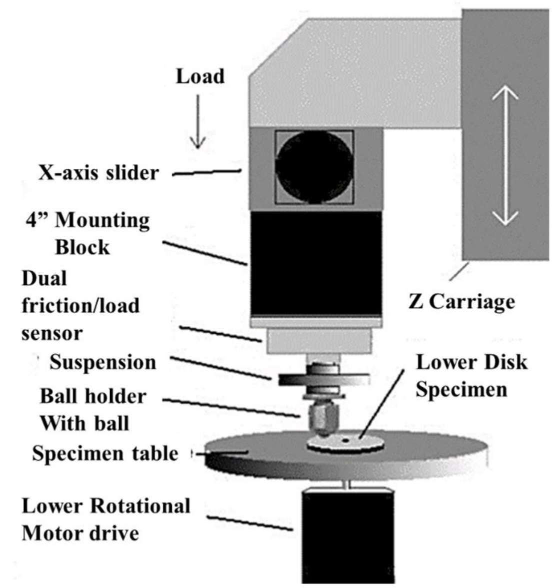

Figure 1. Schematic diagram of a ball-on-disk tribometer [7].

3. Results and discussion

The tribological measurement results obtained from the constant sliding speed of 3600 mm·min^{-1} with the normal forces at 0.1 N and 0.5 N under the test condition of dry and lubricated surfaces are shown in Figures 2 (a)-(c). These selected values of the normal force exerted on the slider correspond to the value of the pressure exerted in the actual slider employed in the HDD fabrication process. From an experiment utilizing a dry AlTiC surface with the applied normal force of 0.1 N, the measured COF fluctuated during the first 50 cycles and then became stable at about 1.276±0.085. As the normal force was increased to 0.5 N, the COF was found to be 0.540±0.052 during the first 50 cycles, before sharply increased and remained at about 1.128±0.052. In the case of dry AlTiC surfaces, an increase of the normal force led to a decrease in the averaged COF. The similar effect was also observed when the lubricated AlTiC surface are covered with an EG-based lubricant. The COF was found to be 0.089±0.115 and 0.065±0.014 when the values of the normal force are 0.1 N and 0.5 N, respectively.

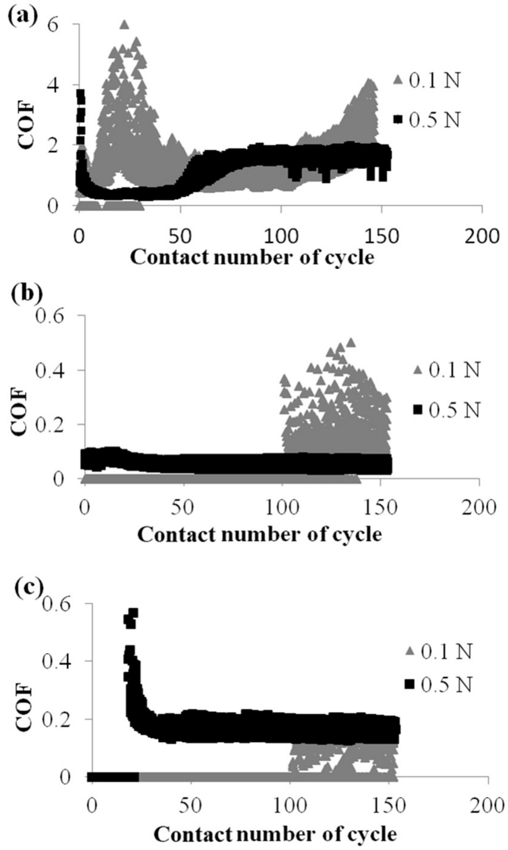

Figure 2. Friction characteristics of the SUS304 ball sliding against the AlTiC surface, under (a) dry surface, (b) with EG-based lubricant and (c) with oil-based lubricant.

However, when the oil-based lubricant was employed in the ball-bearing tribometer experiment, results indicate that an increase in the normal force exerted on the slider caused an increase in the COF values as shown in Figure 2(c). The averaged COF was found to be about 0.033±0.012 and 0.158±0.007 for the values of the normal force at 0.1 N and 0.5 N, respectively. Despite an increase in the COF values due to an increase of the normal force, the averaged COF obtained from utilizing the oil-based lubricant was one order of magnitude smaller than values obtained from an experiment using dry AlTiC plates and about two times smaller than those obtained from an experiment using an EG-based lubricant. COF values of friction occurred at the interface between the slider and the dry and lubricated AlTiC surfaces were shown as a function of sliding speed in Figure 3. It was found that the effect of the normal force on COF value was intertwined with the effect of sliding speed. For instance, when the EG-based lubricant was utilized, COF decreased as a function of the normal force at higher sliding speed (3600 $mm \cdot min^{-1}$). However, at lower sliding speed (300 $mm \cdot min^{-1}$), COF increased as the normal forces increased.

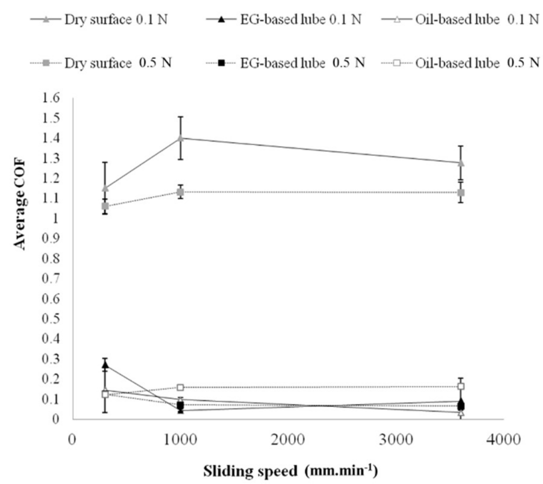

Figure 3. Friction characteristics of the SUS304ball sliding against the AlTiC surface at various applied normal forces, sliding speeds and lubricated conditions.

To identify the friction regime, results were replotted on a logarithmic scale as shown in Figures 4(a)-(c). According to the Stribeck's curve, the relationship between COF and the sliding speed can be used to identify the different regimes of friction. *The boundary friction regime*, where the lubricant is absent or present but the lubricant thickness is much less than the surface roughness, is characterized by the fact that COF is independent of the sliding speed. *The mixed regime*, where the lubricant thickness is comparable to the surface roughness, is observed if COF decreases as a function of sliding speed, whereas *the hydrodynamic friction regime*, where the lubricant thickness is much larger than the surface roughness, corresponds to the regime where COF increases as a function of sliding speed (because of the increasing shear stress between the surfaces) [10]. There have been several theoretical attempts to investigate the relationship between the frictional force exerted on the surfaces and the physical properties of the slider, the plate and the lubricant in the context of ice friction, which the frictional force is viewed as heat generated per unit displacement [9]. Based on the assumption that the lubricating layer is the main source of frictional resistance, the frictional force can be expressed as the product of the shear stress exerted onto the surface and the contact area. According to the further elaborated model of Oksanen and Keinonen [8], a decline of COF as a function of $v^{-1/2}$ (where v is the sliding speed) corresponds to the mixed friction regime, whereas the dependency of the friction coefficient as a function of $v^{1/2}$ is observed in the occurrence of the hydrodynamic friction regime, where the increase in sliding speed leads to a higher shear stress between the two surfaces. As shown in Figure 4(a), COF obtained under a dry condition without using a lubricant is found to be in the boundary friction regime as expected; the friction coefficient does not vary as a function of the sliding speed at both values of the exerted normal force. As represented in Figures 4(b) and 4(c), a utilization of a lubricant led to a one-order-of-magnitude reduction of COF. In addition, as shown in Figure 4(b), when the EG-based lubricant was employed, COF became dependent on the sliding speed, implying that the occurred friction belonged to different regimes [10]. When the normal force of was 0.1 N, COF decreased as a function of the sliding speed in the beginning and, then, increased as a function of the sliding speed (v), indicating a possible regime change from the mixed regime to the hydrodynamic friction regime [10]. A curve-fit of the results on a log-scale indicated that COF decreased as a function of $v^{-1.518}$ in the beginning and then increased as a function of $v^{0.5655}$. The power of 0.5655 is close to the variation as $v^{1/2}$ of the friction coefficient predicted by the model of Oksanen and Keinonen [8] when the occurred friction belongs to the hydrodynamic friction regime where the increasing speed corresponds to an increase in the shear stress. The initial decline of COF as a function of $v^{-3/2}$, however, is not predicted by the same equation or any other model and requires further investigation [8-10].

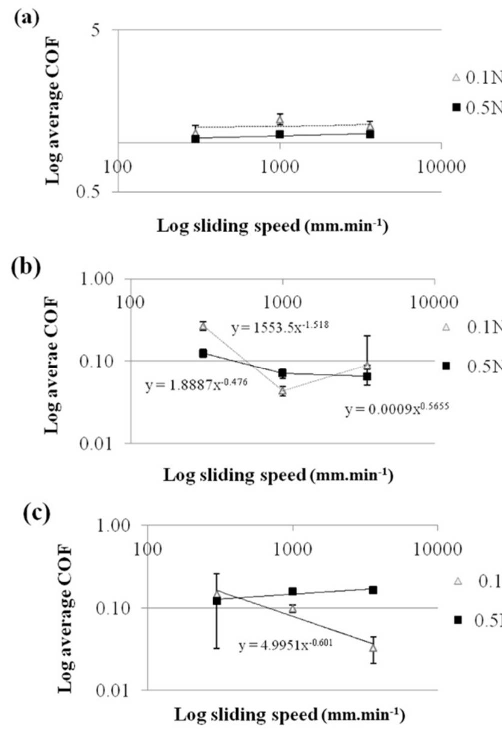

Figure 4. Logarithmic-scale plots of friction characteristics of the SUS304 ball sliding against the AlTiC surface, under (a) dry surface, (b) with EG-based lubricant and (c) with oil-based lubricant.

When the normal force exerted on the ball increased to 0.5 N, the COF started to decrease as a function of the increasing sliding speed. COF values were varied around $v^{-0.476}$. The power of -0.476 was also close to the variation as $v^{-0.5}$ of the predicted friction coefficient in the mixed friction regime where the lubricant thickness was comparable to the surface roughness. As the sliding speed increased, the COF became constant and independent of the sliding speed, indicating a possible transition from the mixed friction regime to the boundary friction regime. We speculated that this might be due to the decreasing of the lubricant thickness at high sliding speed, resulting in the lubricant thickness change from being comparable to the surface roughness (the mixed friction regime) to being smaller than the surface roughness (the boundary friction regime).

For the AlTiC surface covered with the oil-based lubricant when the normal force is 0.1 N, the COF monotonically decreased as a function of $v^{-0.601}$. This power relationship is close to the theoretical prediction of Oksanen and Keinonen [8] where the COF decreases as $v^{-0.5}$ in the mixed friction regime. As the normal force was increased to 0.5 N, the COF values were independent from the sliding speed suggesting that the friction might belong to the boundary friction regime. This might be due to a deeper wear on the AlTiC surface brought about by an increasing of the exerted normal force. Those surface wear tracks were found on the AlTiC surface from the inspection using (SEM).

As seen from electron micrographs shown in Figures 5(a)-(f), in the case of the dry AlTiC surface, the deep wear tracts have been observed on the surface and became wider but seemingly less deep as the normal force was increased from 0.1 N to 0.5 N. Much shallower wear tracts were observed for EG-based lubricated surface. Larger and deeper wears (although not as deep as those obtained from the dry surface condition) were also been observed as the oil-based lubricant was implemented on the AlTiC surface. This may be due to the fact that the friction regime in this oil-based lubricant case belonged to the mixed friction regime at the exerted normal force of 0.1 N and transferred to the boundary friction regime, as the normal force was increased for 5 times.

In the experiment of Zhou et al. [11], the ball-bearing tribometer was also employed; a Si_3N_4 ball slid against an Al_2O_3 surface with the fluid between the surfaces being air, water and oil. The normal forces exerted on the sliding ball were higher at 5-10 N, likewise the sliding velocity is higher at 3,000 -9,000 $mm \cdot min^{-1}$. When the lubricant is either water or oil, COF declined as a function of sliding speed if the normal force is 5 or 7.5 N. With increases in the normal force and the sliding speed, COF in air increased whereas COF in oil and water decreased [11]. In contrast, in our experiment where an Al_2O_3 ball moved on an AlTiC plate, the effect of normal force and the sliding speed on the COF were intertwined as discussed earlier. For instance, when the lubricant was oil-based, the COF decreased as a function of the normal force when the sliding speed was small as observed earlier by Zhou et al. [11] but increased as the normal force increases when the sliding speed was larger. This might be due to the fact that the COF declined as a function of $v^{-0.5}$ when the normal force was 0.1 N as theoretically predicted for friction in the mixed friction regime, but became independent of sliding speed as typically observed for friction in the boundary friction regime when the normal force was 0.5 N.

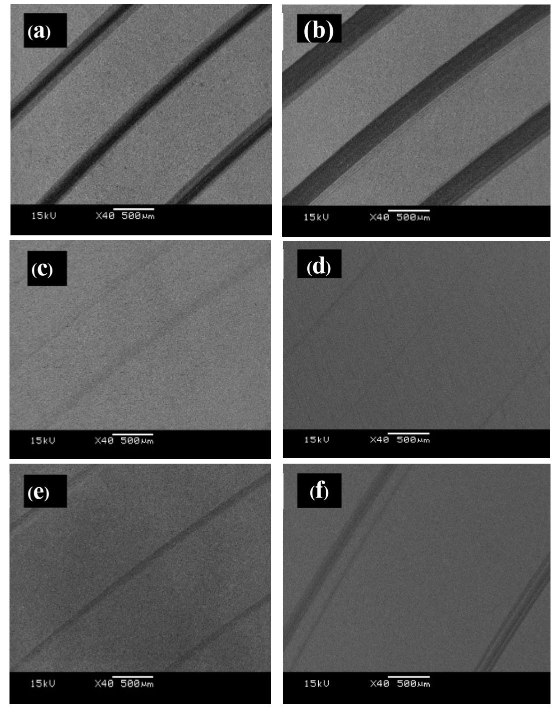

Figure 5. Electron micrographs of the AlTiC surfaces after tribological measurements under surface conditions and forces of (a) dry surface at 0.1 N, (b) dry surface at 0.5 N, (c) lubricated with EG-based lube at 0.1 N, (d) lubricated with EG-based lube at 0.5 N, (e) lubricated with oil-based lube at 0.1 N, and (f) lubricated with oil-based lube at 0.5 N. Note that all the samples were from the sliding speed of 3600 rpm.

4. Conclusions

The tribological characteristics and friction regimes of both dry and lubricated AlTiC surfaces were investigated at various load forces, sliding speeds and types of lubricant. All tribological studies were done by using a ball-on-disk tribometer. The COF values were extracted and analyzed using power law theory of ice friction. For dry surface, the friction behavior was found to be in boundary regime. For the lubricated AlTiC surface with an EG-based lubricant, the friction regime depended on both normal force and sliding speed. In contrast with the oil-based lubricants, the COF depended on the sliding speed only at low normal force. The different normal load forces led to different friction regimes. SEM investigation indicated that the mechanism of wear was an abrasive wear. The results have important implications in lubricant design specifically for lapping process in HDD slider fabrications.

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